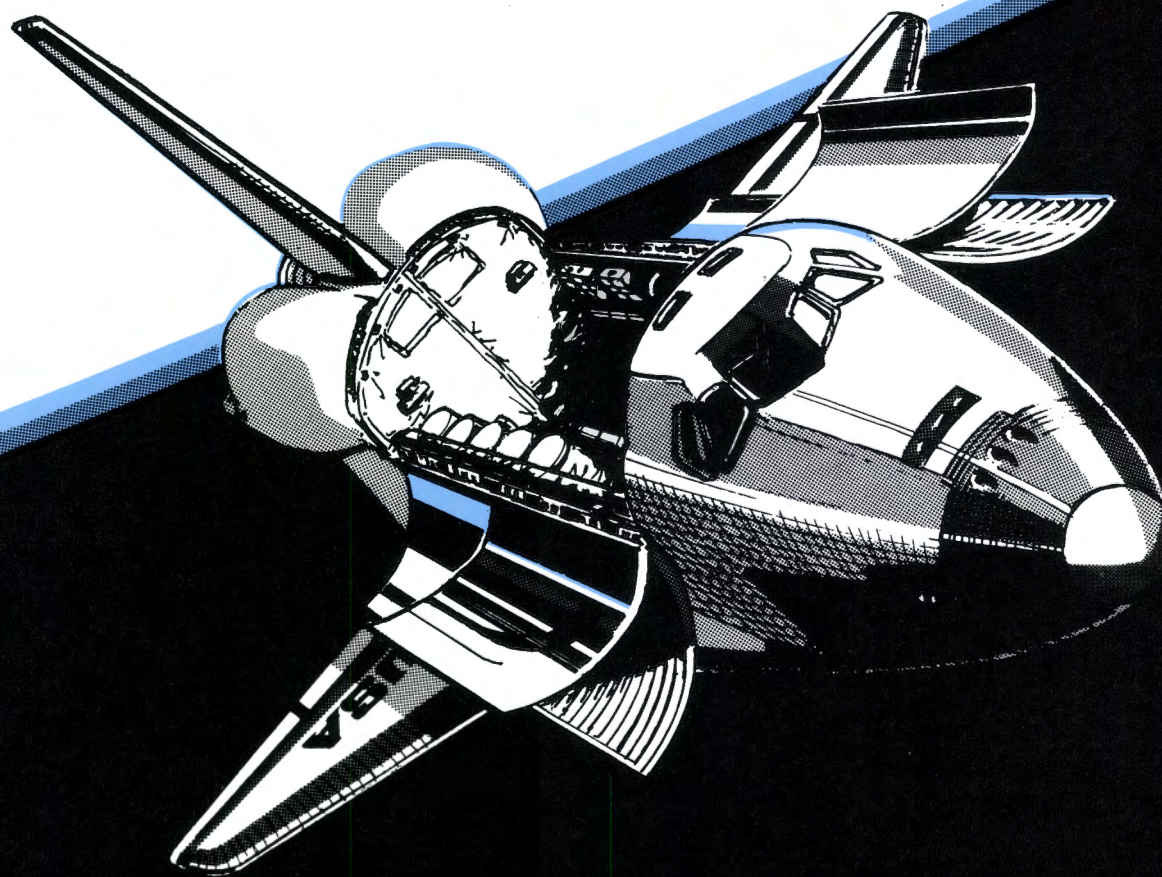


TANK PRESSURE CONTROL EXPERIMENT ON THE SPACE SHUTTLE



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INTRODUCTION

New technology for managing cryogenic fluids in low gravity will be required for future space systems such as space transfer vehicles, Space Station Freedom, serviceable satellites, hypervelocity aerospace vehicles, and space defense systems. The purpose of the tank pressure control experiment is to provide some of the low-gravity data needed for the development of that technology.

A goal of the National Aeronautics and Space Administration is to establish cooperative efforts with United States industry to use the Space Transportation System (Space Shuttle) for advancement of our space utilization and exploration technology base. This experi-

ment is being developed under the NASA In-Space Technology Experiments Program (IN-STEP) within the technology theme area of propulsion and fluid management. Funding for this project is being supplied by the NASA Office of Aeronautics and Space Technology. The prime contractor for the tank pressure control experiment is Boeing Aerospace; the subcontractor is Washington University. Globesat, Inc. and Quartic Systems, Inc. are the primary vendors for the experiment. The project is managed by the NASA Lewis Research Center. The experiment is scheduled to fly on the Space Shuttle in late 1990.

TECHNICAL BACKGROUND

Many future space missions will require the use of large quantities of cryogenic fluids. High-energy liquid hydrogen-oxygen propulsion systems will likely be required for space-based transfer vehicles and manned lunar and Mars missions. These propulsive stages will be filled and refilled at an orbiting propellant depot, which itself will be periodically resupplied by ground-based tankers. Other potential users of large quantities of cryogenics include Space Station Freedom (subcritical nitrogen for cooling, atmospheric makeup, and other uses), space defense systems (cryogenic resupply), and space-based sensors (cryogenic coolants). These applications will require storage of cryogenic fluids for greater lengths of time than have been necessary or feasible to date, and some of them will also require on-orbit refill. Advanced concepts and techniques will be required for storing and handling these cryogenic fluids.

Any tank of cryogenic liquid stored in space is subject to heat leaks, often at varying rates and with a non-uniform distribution around the tank. These heat inputs raise the tank pressure by heating and evaporating some of the liquid and by heating the vapor. The rate at which the pressure rises depends strongly on the distribution

of the heat within the fluid. Since the tank pressure is controlled by the vapor pressure of the warmest liquid in the tank, a nonuniform temperature distribution results in higher pressure than would be found with an isothermal fluid. Localized "hot spots" therefore drive the pressure up faster and to higher levels. If the heat input is instead uniformly distributed throughout the fluid, the pressure rise is minimized. The pressure rise rate in a tank of well mixed cryogen may be an order of magnitude less than if the contents are not well mixed. Reliable control of tank pressure is essential to the storage and handling of cryogenic fluids in space.

In the low-gravity space environment, fluid mixing due to free convection is greatly reduced. This allows hot spots and steep temperature gradients to form. In low-g the resulting pressure increase cannot be relieved by the conventional venting of vapor (due to uncertainty about the location of the vapor), but must be controlled by thermodynamic means. For short-term storage periods (such as the several days that might elapse between Shuttle launch of a stage and its firing), mixing alone could be an adequate means of controlling pressures. Based on prior work, it appears that a

relatively small amount of induced liquid motion is sufficient to break up the hot spots and provide forced-convection heat transfer coefficients that are several orders of magnitude higher than predicted for free convection in low gravity. The benefits to space cryogenic systems of active mixing are that it (1) reduces pressure-rise rate in a nonvented tank, (2) enables the use of compact heat exchangers, (3) can serve as backup for passive cooling systems, (4) may reduce on-orbit fluid transfer time, and (5) ensures delivery of uniform-temperature liquid for transfer to another tank or to the engines of a propulsive stage.

Mixing systems can be built that provide adequate circulation; the problem is to mix efficiently as well as reliably. Mixers designed for use in previous cryogenic space systems were based on extensive ground testing with a great deal of oversizing provided to compensate for the lack of knowledge about low-g mixing behavior. The penalty for this conservatism is that the energy used

by the device eventually dissipates as heat in the fluid, resulting in an increase in the overall heat input to the fluid. Therefore, there is a strong need to optimize the kinetic energy added by the mixer since this largely determines the pumping power.

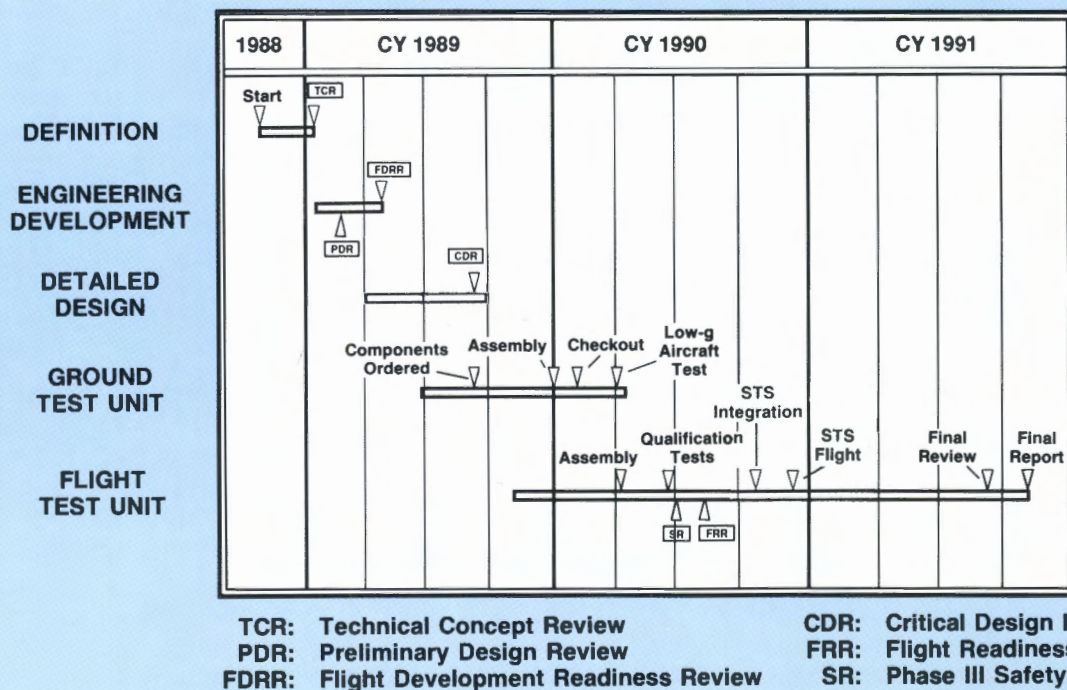
In addition to increased overall heat input, there are other penalties for oversized mixers. The size, mass, cost of the mixing device and its power supply must be considered. For example, there is some potential for undesirable fluid dynamic forces on vehicles when a high-velocity jet is employed. Particularly when the liquid/vapor orientation is not symmetric, the momentum imparted to the liquid by the jet will cause a reaction force that could reorient the vehicle. Low-velocity, low-kinetic-energy jet mixing, however, is unproven in its effectiveness with a low-g fluid orientation. Until adequate low-g data is available, mixers will be sized conservatively (overdesigned) and the resulting penalties will be incurred.

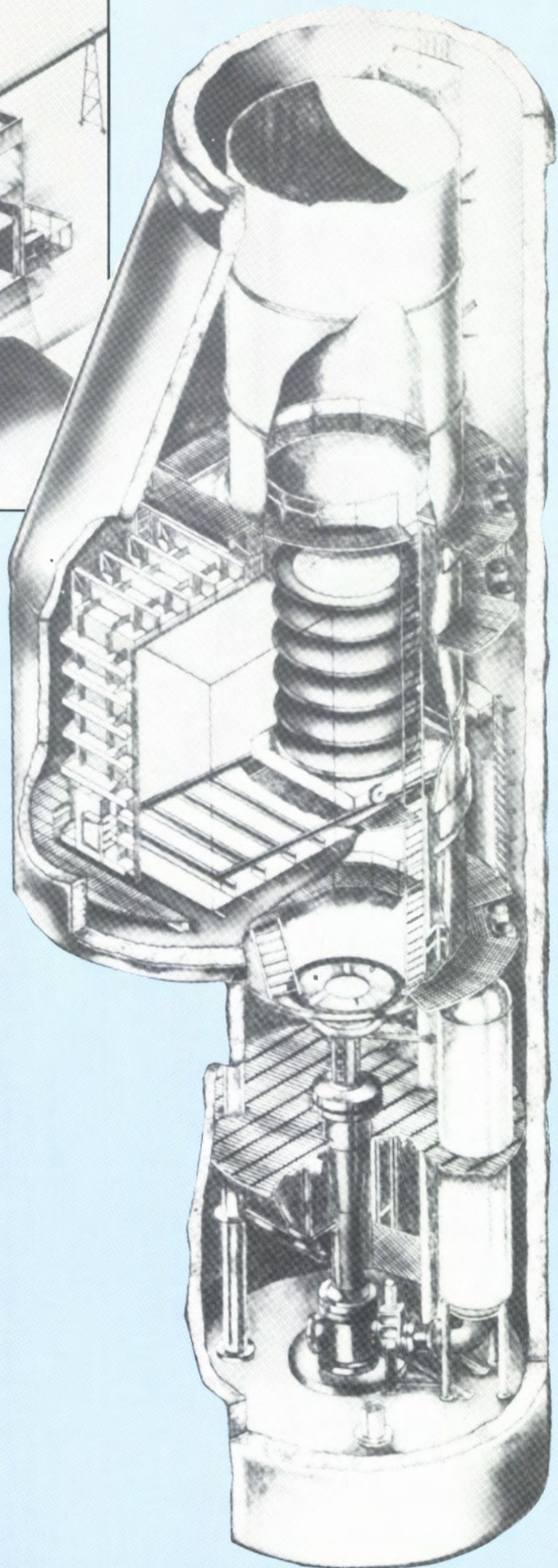
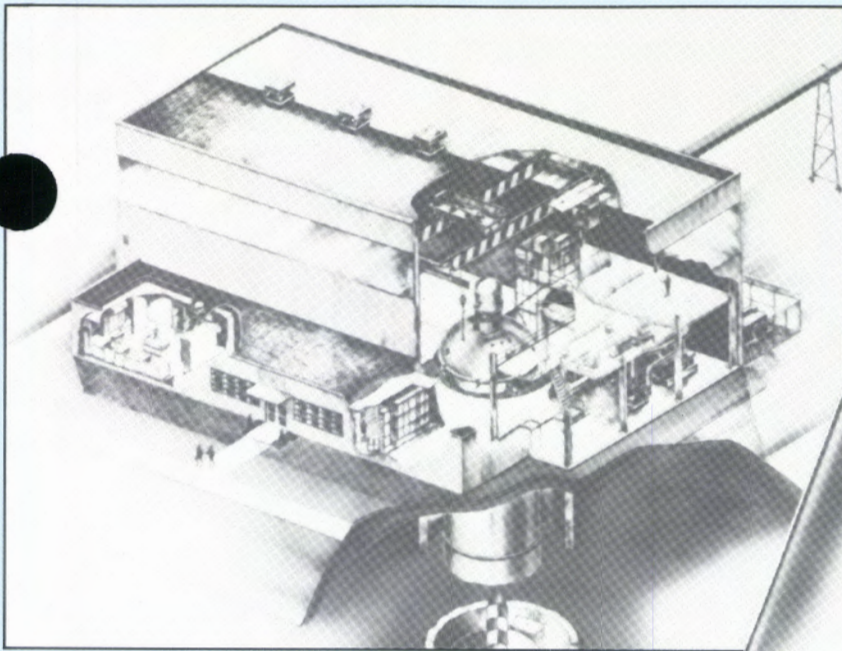
PROJECT OBJECTIVES

The tank pressure control experiment will study the fluid physics and thermodynamics of jet-induced fluid mixing of cryogens in low gravity. This experiment will measure how jet-induced fluid mixing reduces tank pressure and will produce data on low-gravity mixing processes critical to the design of on-orbit cryogenic storage and resupply systems. The objectives of the experiment are to (1) characterize the fluid dynamics of jet-induced fluid mixing in low gravity, (2) evaluate the

applicability of existing empirical mixing models and correlations to thermal mixing in low gravity and, if appropriate, derive new or modified correlations, and (3) identify approaches to enhancing the ECLIPSE (Energy Calculations for Liquid Propellants in a Space Environment) computer code now under development by Washington University for NASA to simulate phase fluid dynamics and thermodynamics.

SCHEDULE OVERVIEW





HISTORY

The foundations for conducting this low-gravity flight experiment are tests performed in drop towers at the NASA Lewis Research Center in the late 1970's and ground-based testing at Boeing Aerospace in the early 1980's. Those efforts provided several mixing-time correlations, a method of predicting jet flow regimes in low gravity, and mass transfer rates in normal gravity. The tank pressure control experiment was conceived in 1985 to provide an extension of these efforts to the low-gravity environment. The experiment concept evolved to a mature stage through critical assessments by Boeing Aerospace and NASA engineers. In the definition stage, preliminary designs of critical components of the experiment were begun.

In December 1986, Boeing Aerospace submitted a proposal to NASA to begin the development phase of the tank pressure control experiment under the NASA OAST Outreach Program. The experiment was selected for funding, and a contract to proceed with the flight hardware development was signed on November 15, 1988. The Cryogenic Fluids Technology Office at the NASA Lewis Research Center was assigned responsibility for the technical management of the contract.

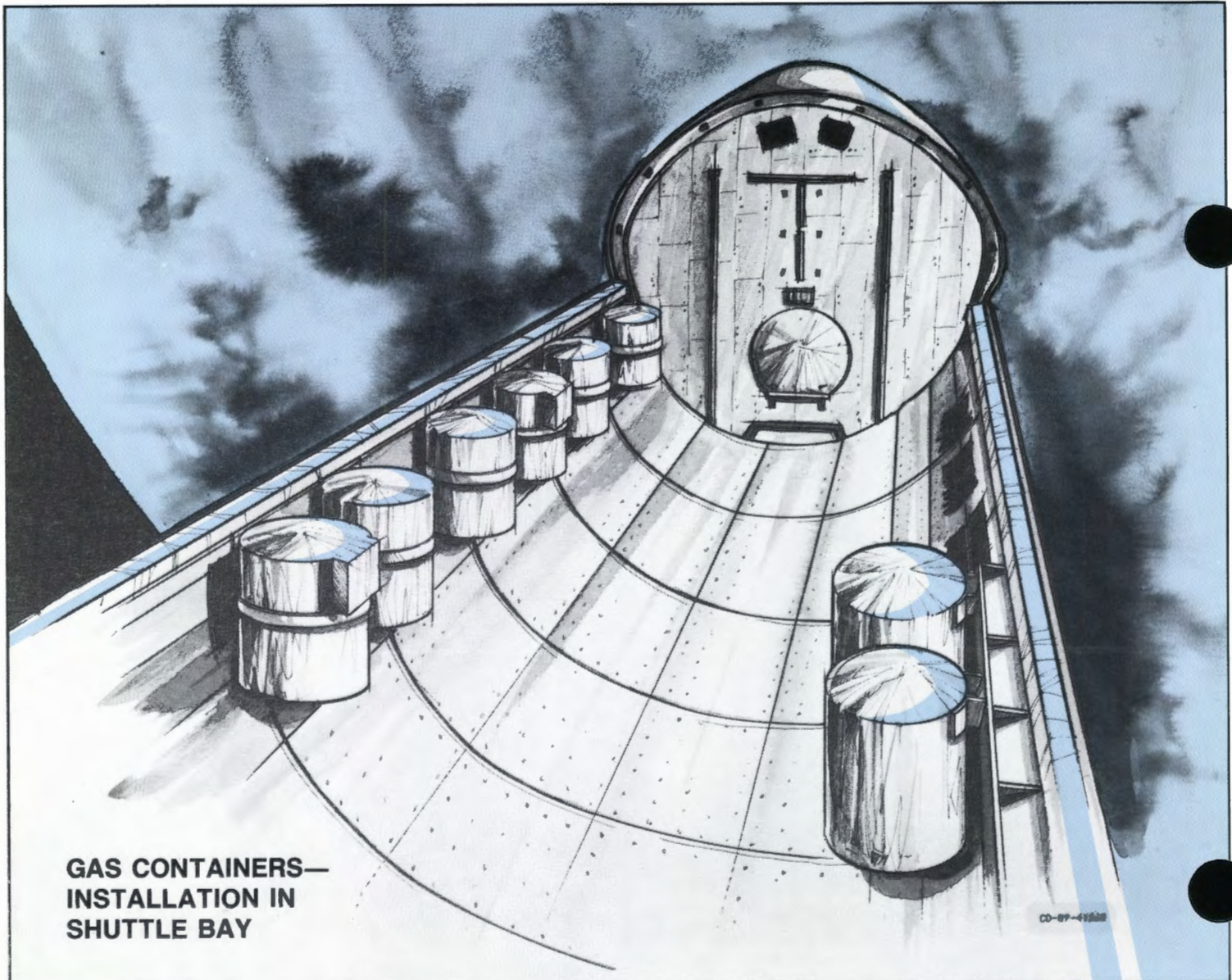
JUSTIFICATION

Basic data on low-gravity fluid motion and thermodynamics is extremely rare, in spite of the fact that such data is critical to the development of space transfer vehicles and spacecraft resupply facilities. An in-space experiment is needed to obtain reliable data on fluid mixing and pressure control because none of the available microgravity test facilities provide a low enough gravity level for a sufficient duration to duplicate in-space flow patterns and thermal processes. Normal gravity tests do not represent the fluid behavior properly; drop-tower tests are limited in length of time available; aircraft low-gravity tests cannot provide the extremely low-gravity level and long duration needed to study the subtle processes expected in space.

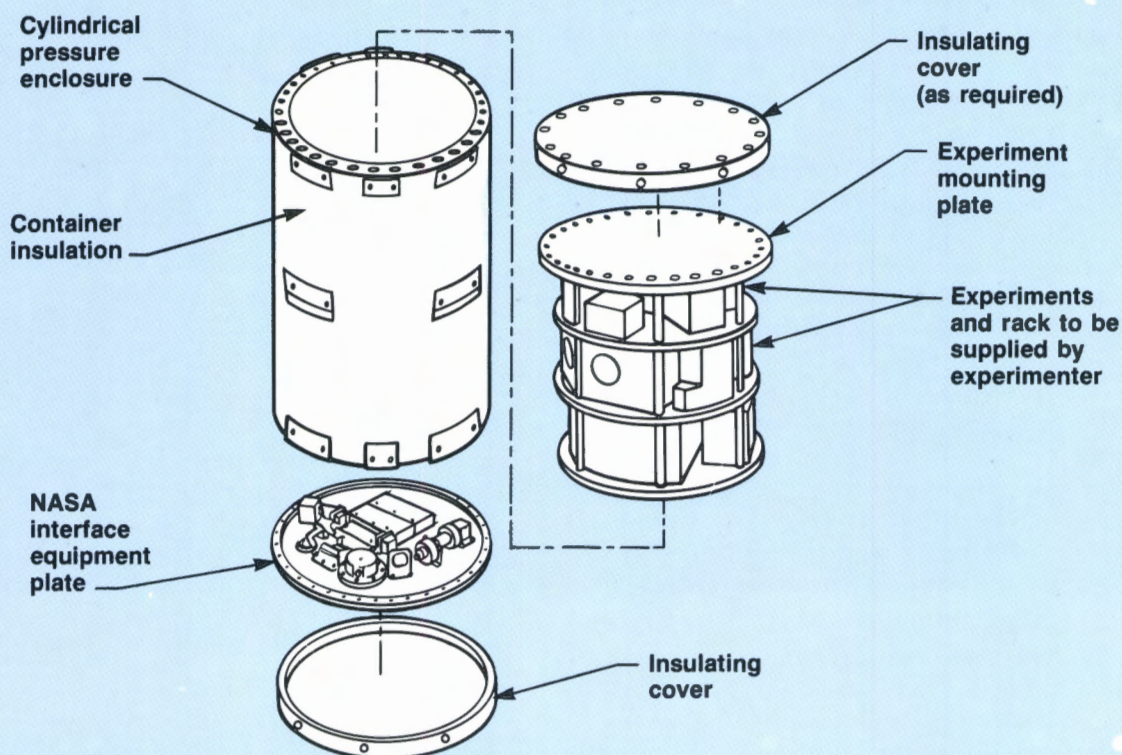
The experiment measurements will be used to extend existing mixing correlations which will help in predicting heat and mass transfer rates in the low-gravity environment. The measurements will also help validate NASA

computer models of fluid behavior in low gravity. The video data (the motion of the liquid-vapor interface in response to mixing) will be used to characterize the flow patterns. The experiment results will later be useful in generating essential design and performance specifications for future low-gravity fluid management systems. Without this information, future space systems would pay significant weight penalties in the form of overly conservative mixers, extra cryogen boiloff, or settling rockets as a result of inadequate knowledge of mixer performance in low gravity.

This experiment will also benefit the NASA Lewis Research Center's COLD-SAT program (Cryogenic On-Orbit Liquid Depot-Storage, Acquisition, and Transfer) by producing timely results useful in the development of that program. It will provide data needed to validate the low-gravity fluid simulation codes developed by the Cryogenic Fluids Technology Office at Lewis.



CONTAINER CONCEPT



DESCRIPTION

The experiment will simulate the behavior of cryogenics in a low-gravity environment by using Freon at saturated conditions as the test fluid. Pressure, temperature, and video data will be collected as the liquid in the test tank is alternately heated locally (stratified) with heaters and mixed with a pump. The payload carrier will be a Get Away Special (GAS) container, and Shuttle integration will be done within the Complex Autonomous Payloads (CAP) program, which is managed by the Goddard Space Flight Center.

The principal element in the GAS concept is a standardized aluminum container (cylindrical pressure enclosure) that provides complete containment for the experimental equipment, thus making safety assurance comparatively easy. The GAS container can be purged with dry nitrogen and sealed, filled with an inert gas, or opened to the Shuttle environment. Normally the containers are mounted to the side of the cargo bay, but

a GAS bridge that spans the cargo bay and is capable of holding 5 to 12 GAS containers has been developed and is occasionally carried in the Shuttle.

The Shuttle provides no telemetry or power to the GAS container. Three latching relays provide toggle switch control for instrument activation/deactivation and operational mode changes. Commands are issued and verified by the crew through a hand-held encoder. The commands are sent "party-line fashion" to all containers via a twisted shielded pair and are interpreted within each GAS container by a control decoder.

The circular end plates of the container are used for equipment mounting. The bottom plate is the interface equipment plate. The top plate is the experiment mounting plate. The inner surface of this plate has a hole pattern adaptable to mounting a variety of hardware. The sides and bottom of the container are insulated; the top will also be insulated for this flight.

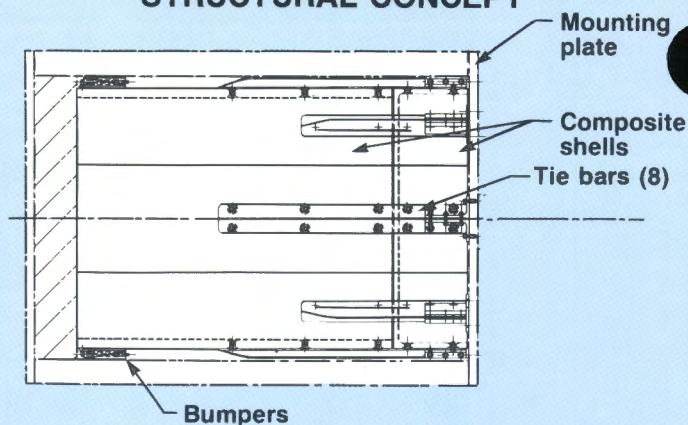
FLIGHT HARDWARE

The experiment encompasses primarily the test fluid, tank, mixer, dual video cameras, sensors, and control computer. Freon 113 (a nontoxic and nonflammable refrigerant) has been selected as the test fluid because it has usable vapor pressures over the wide range of temperatures that a GAS payload can experience.

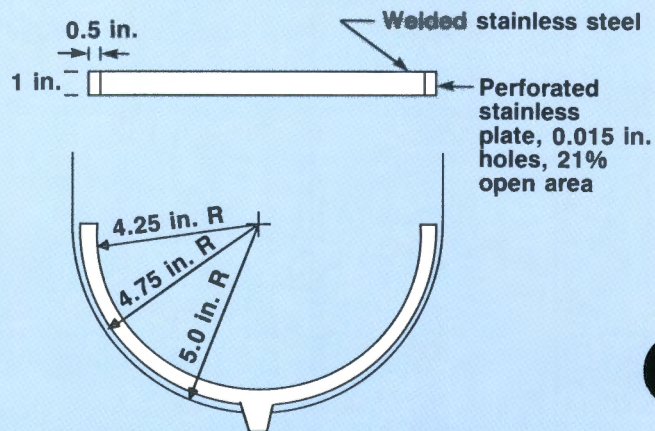
The tank size chosen has the largest volume possible within the GAS container constraints; its dimensions are representative of the relative shape of standard propellant tanks. Plexiglas was chosen for the tank walls as a result of long-term tests of the effect of Freon 113 on various plastics; also, it will allow for recording the motion of dyed Freon within the transparent tank. The two halves of the tank will be sealed to a steel ring, to which all attachments and tank penetrations will be mounted. The tank will be oriented so that the orbital drag of a nominal mission is aligned with the tank axis. The tank pressure is expected to range from 2 to 15 psia; since the GAS container will be pressurized with nitrogen to 15 psia, the tank will not be at high relative pressure.

An 85-percent fill level was selected to model the small-ullage condition, which is the most demanding for pressure control during storage (because of the sensitivity of pressure to the generation of vapor). Two heaters will be provided so that one can heat the ullage (or produce a bubble at the tank end opposite the mixer nozzle) and the other can create a nonaxisymmetric bubble (simulating a local hot spot on the wall). Six thermistors will be oriented to measure temperature gradients and, for some runs, the temperature history of the ullage.

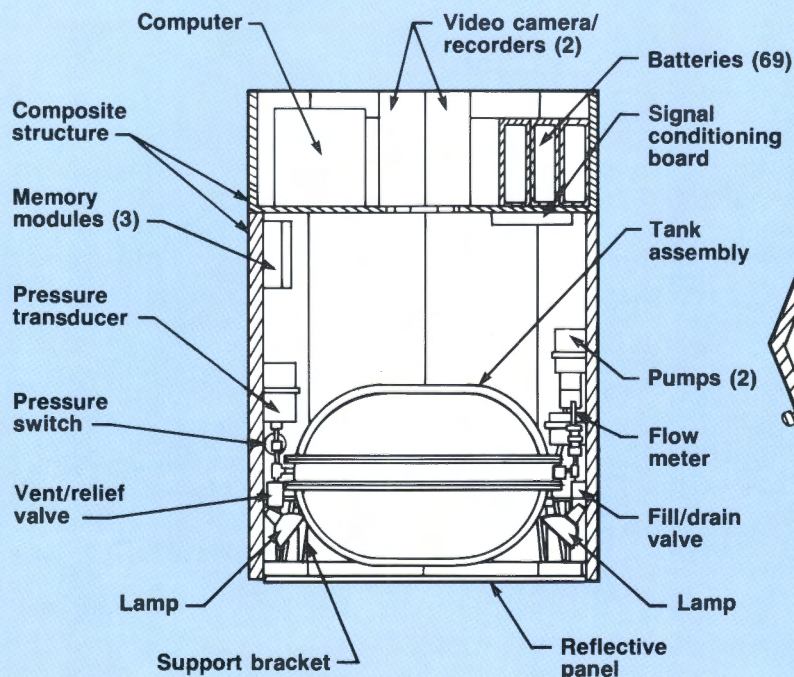
STRUCTURAL CONCEPT



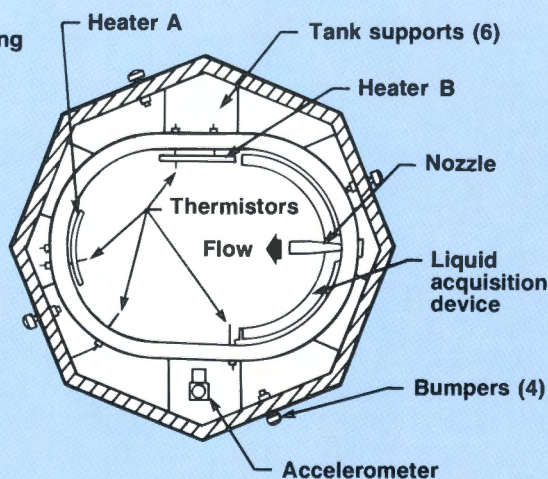
LIQUID ACQUISITION DEVICE



EXPERIMENT CONFIGURATION



CUTAWAY VIEW



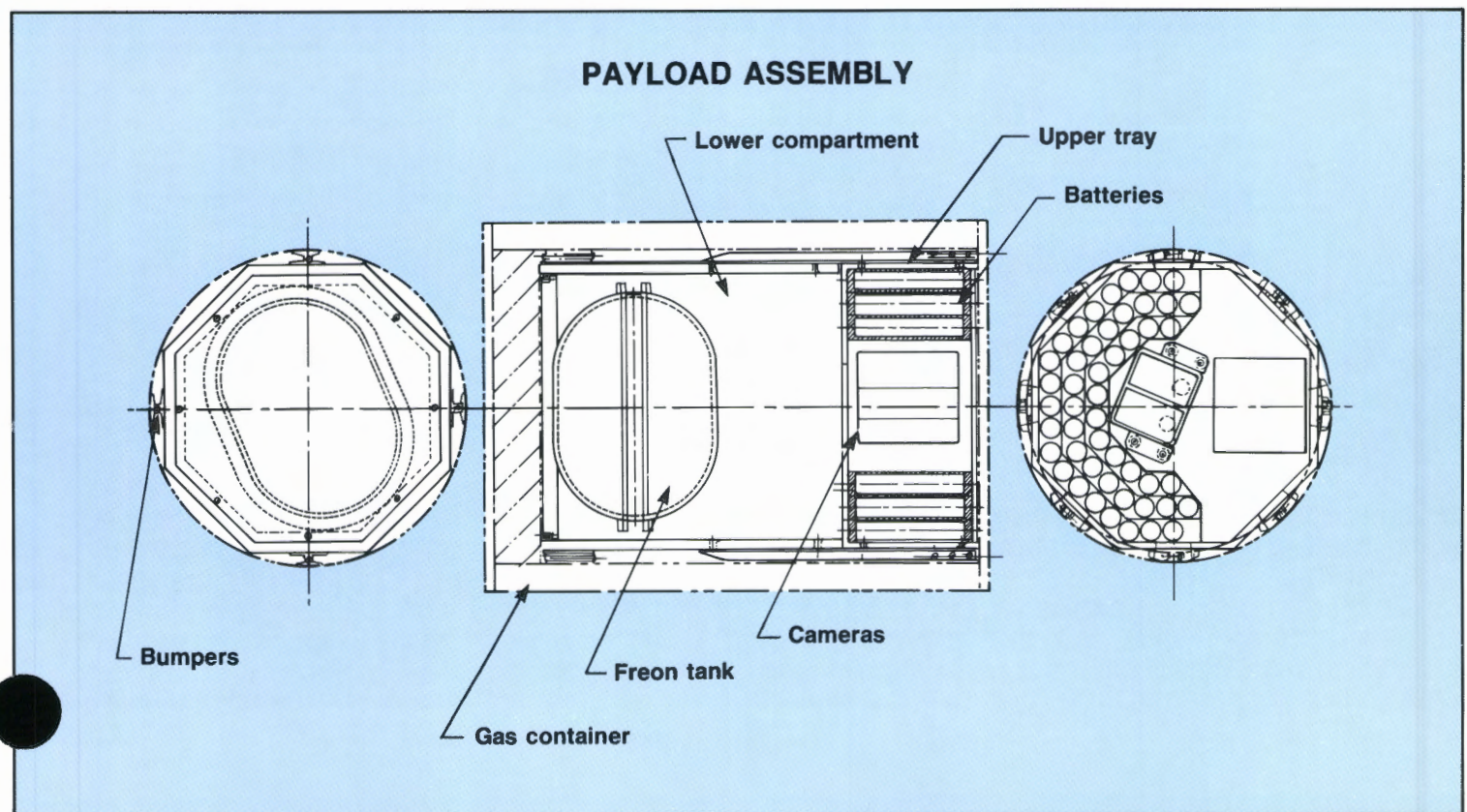
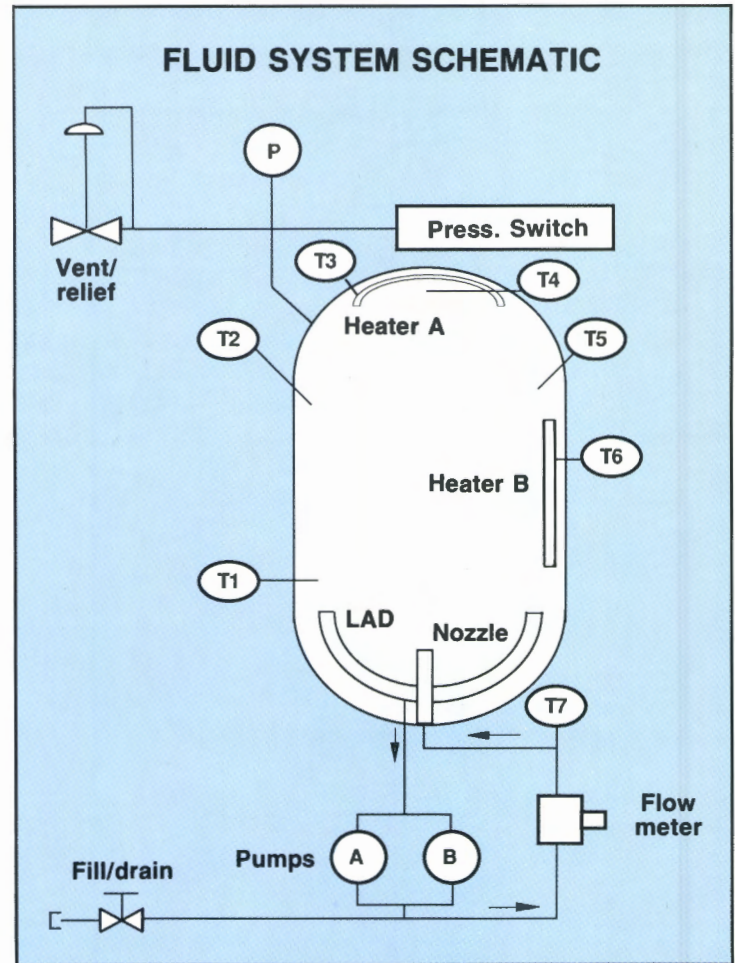
Note: For clarity, some components are not shown in their true orientations

A mixer pump will be located outside the tank to allow flow metering and easy packaging. Liquid will be withdrawn from the tank through a liquid acquisition device (LAD), a channel with a finely perforated wall that uses surface-tension forces to prevent ingestion of vapor. After passing through the pump and flowmeter, the liquid will reenter the tank through an axial nozzle.

Measurements will be made of pressures, temperatures, flow rates, and accelerations using standard instrumentation.

All these components will be mounted within a structural shell made of foam-fiberglass sandwich material. This inexpensive and strong design has been used successfully in previous GAS payloads. The composite pieces will be connected together and to the GAS container mounting plate with four external aluminum beams.

Commercial alkaline cells will be used for the electrical power supply because of their relatively high energy density, long shelf life, and prior use on the Shuttle. Also, their low cost means that replacement after each of several full-up tests is less expensive than the initial purchase of rechargeable cells. Enough battery capacity is planned to meet the energy requirement of approximately 450 watt-hours, plus a 25 percent contingency power supply. Ample battery margin will minimize voltage fluctuation and ensure adequate energy for the payload.



TEST MATRIX

The primary points consist of three runs each on Heater A and Heater B for mixer flow rates of 0, 0.15, 0.40, and 0.70 gallons per minute. Each of these primary points is run three times to assess the repeatability of the data and to experience various fluid orientations. The secondary points consist of one run each at flow rates of 0.08, 0.20, 0.30, 0.50, and 1.0 gallons per minute for the same heater configurations and one run at flow rates of 0, 0.15, 0.40, 0.70 for the two heaters combined. These 38 points will be taken in a preselected order over a 25-hour period, ensuring that some are taken during a quiescent crew sleeping period. Each run consists of heater operation for 10 minutes, or until pressure rises 3 psi, and mixer operation for 15 minutes, with a 15-minute wait between runs to let the fluid become quiescent and settled. The video cameras will record the fluid orientation prior to and during the first minute of operation of the heater(s) and will be turned on again

shortly before initiation of mixing for a total of 6 minutes of video data per test run. The thermodynamic data will be recorded throughout the 25 hours of the experiment.

		MIXER FLOW RATE (GPM)									
		0	0.15	0.4	0.7	0.08	0.2	0.3	0.5	1.0	
Heater A (25W)		3	3	3	3	1	1	1	1	1	
Heater B (25W)		3	3	3	3	1	1	1	1	1	
Heater A&B (12.5W total)		1	1	1	1						

24 Primary runs
14 Secondary runs
38 Total

TEST PARAMETERS

MEASUREMENT	RANGE	ACCURACY	RESPONSE TIME
Tank Pressure	0 to 20 psia	0.05 (0.25%)	0.5 sec
Heater Power	0 to 25 W	0.5 W (2%)	1 sec
Temperature	15 to 110 °F	0.2 (0.2%)	< 2 sec
Flow Rate	0.08 to 1.0 gal/min	0.02 (2%)	1 sec
Accelerations	-0.02 to +0.02 g (3 axes)	5x10 ⁻⁴ (3%)	0.1 sec
Liquid/Vapor Location/Orient.	full view of tank		0.5 sec

The test hardware will provide for collection of pressure, temperature, and video data. The specific flight data to be obtained include

- Tank pressure time responses
- Fluid temperature time responses at six locations
- Mixer flow rates
- Heater power and on times
- Video records of liquid-vapor interface motion
- Accelerations (background and spikes) during tests
- Temperatures outside the tank
- Mission timeline and orbiter attitudes (data from NASA-JSC)

DATA RECORDING

A microcomputer will be used to control the experiment and record the data. Custom input and output boards will provide the interfaces to the instrumentation, pump, heaters, camera, and lights, and the data will be recorded in a 3-megabyte, solid-state memory. A PC will be used to develop the software, load it onto the controller/recorder, and read the data from the experiment memory onto disk after an experiment run.

A pair of video camcorders will be used to record part

of each experiment run, with a total of 4 hours on the tape (2 hours by each camera). The tank will be backlit by halogen lamps reflecting off a white background with a rectangular grid marked on it. The Freon will be tinted with Sudan IV dye to provide contrast between the liquid and vapor, thereby showing the interface between them. A consumer-model video recorder will be used because of its ruggedness and small size.

Report Documentation Page

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16. Abstract The tank pressure control experiment is a demonstration of NASA intent to develop new technology for low-gravity management of the cryogenic fluids that will be required for future space systems. The experiment will use Freon as the test fluid to measure the effects of jet-induced fluid mixing on storage tank pressure and will produce data on low-gravity mixing processes critical to the design of on-orbit cryogenic storage and resupply systems. Basic data on fluid motion and thermodynamics in low gravity is limited, but such data is critical to the development of space transfer vehicles and spacecraft resupply facilities. An in-space experiment is needed to obtain reliable data on fluid mixing and pressure control because none of the available microgravity test facilities provide a low enough gravity level for a sufficient duration to duplicate in-space flow patterns and thermal processes. Normal gravity tests do not represent the fluid behavior properly; drop-tower tests are limited in length of time available; aircraft low-gravity tests cannot provide the steady near-zero gravity level and long duration needed to study the subtle processes expected in space.					
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DATA ANALYSIS

Following the flight, the raw data stored in memory chips will be copied onto floppy disks using a PC linked to the controller/recorder computer. The binary data will be converted to data in engineering units and then compiled, plotted, and summarized. The data from the test runs will include fluid flow patterns, pressure and temperature responses, and accelerations. Nondimensionalized mixing parameters will be plotted as functions of time, Reynolds number, Bond number, Weber number, etc.

Pressure and temperature decay rates, mixing times, and flow regimes will be compared with results calculated from empirical correlations developed by previous investigators. The thermodynamic data (temperatures and pressures) will be reduced further to yield estimates of heat and mass transfer rates at the liquid-vapor interfaces. These will be compared as functions of the mixer parameters to the 1-g-based relationships currently in use. The video tape will be used to relate the results for the data analysis with a physical observation of the events.

Also from the video data, the observed fluid dynamics will be classified in distinct patterns or types that depend on the jet-mixer flow rate and possibly on the initial location of the ullage bubble or bubbles. Using these

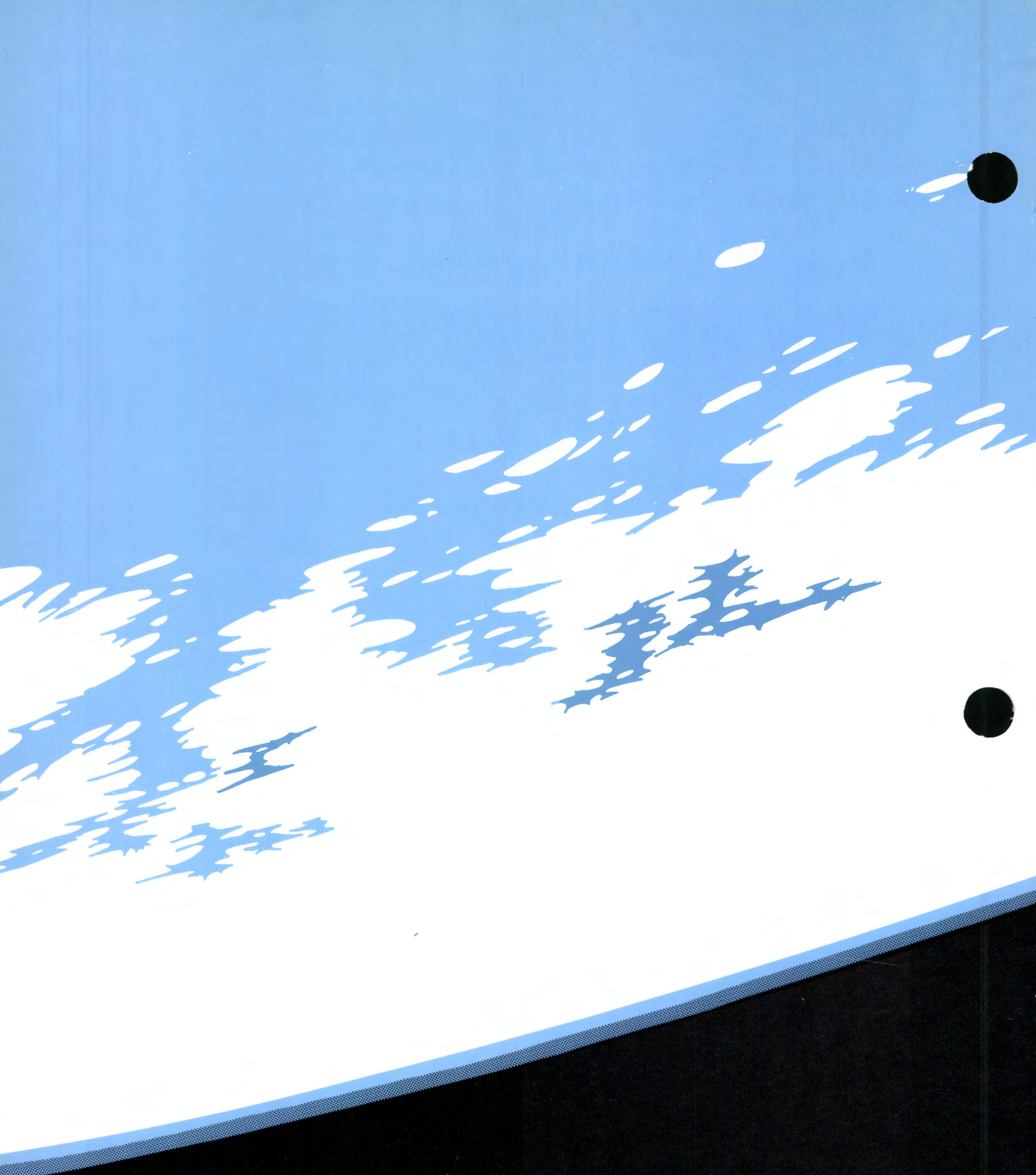
data in combination with the existing small-scale drop-tower data obtained at NASA Lewis, an empirical correlation relating the flow patterns to nondimensional parameters that characterize the mixer flow, tank geometry, acceleration level, and fluid properties will be established.

The ECLIPSE computer code is being developed under grant to Washington University. The code is an expansion of the NASA-VOF2D code for simulating laminar, isothermal fluid motion in low gravity and incorporates the effects of turbulence, heat transfer, and changes of state. Washington University personnel will use the space flight data for comparison with the computed flow pattern and pressure transients. For selected experiment runs, actual in-space fluid initial conditions will be used as inputs for postflight ECLIPSE simulations in the event that the actual conditions differ significantly from those assumed for the preflight simulations. If the output of ECLIPSE does not match the data satisfactorily, Washington University will identify which physical effects are not represented well in the code to help guide further code development. This use of the tank pressure control experiment data to help with further code development is expected to be an important benefit of the experiment.

For further information, contact—

R.H. Knoll
LeRC Project Manager
NASA Lewis Research Center
21000 Brookpark Rd.
Cleveland, OH 44135
(216) 433-2419

Dr. J.S. Meserole
Boeing Project Manager
Boeing Aerospace
P.O. Box 3999
Seattle, WA 98124
(206) 773-2678



National Aeronautics and
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Lewis Research Center
Cleveland, Ohio

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